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**SEMICONDUCTOR OPTICAL DEVICE HAVING ASYMMETRIC RIDGE
WAVEGUIDE AND METHOD OF MAKING SAME**

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Field of the Invention

The present invention is directed generally to a semiconductor device, and more particularly to a semiconductor device with an asymmetric ridge waveguide.

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Background

Optical fiber communications have been a commercial reality now for over twenty years. Research and development efforts still continue to explore new laser sources, new forms of optical amplifiers, novel materials for low-loss optical fibers, and the like. At present, long-haul fiber optic communication systems employ small core (on the order of a few microns) single-mode fibers used in conjunction with laser diodes also operating in their single-mode regime, typically the lowest order transverse mode. This configuration yields low intermodal dispersion and allows for what is commonly called dense wavelength multiplexing (DWDM).

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Today, low-loss single mode fibers and laser diodes that operate near optimum wavelength for low loss propagation are readily available. Even so, in-line optical amplifiers (all-optical repeaters) are necessary approximately every 400 kilometers (\cong 250 miles) or so for long haul applications. One such in-line

optical booster is the erbium-doped fiber amplifier. This device is capable of simultaneously amplifying multiple wavelengths (multiple optical channels) by optically pumping from a secondary pump laser operating at a shorter wavelength. Notwithstanding these advances, research is still underway to

5 increase the distance between optical repeaters. One approach is to increase the optical energy from the pump laser coupled into the fiber. Practical challenges arise from this approach. First, laser diodes driven at high input currents may transition from single-mode to multimode operation, indicative of the so-called "kink effect" in the light output versus injection current

10 characteristic. Although the laser may have more total output optical energy in the multi-mode state, there are at least two negative drawbacks to this straightforward approach. First, when lasing in the multi-mode regime, the optical energy is less confined near the optical axis of the laser and more divergent as the beam exits the laser end-face. Given this, the coupling

15 efficiency for focusing the laser output into a fiber is reduced. Secondly, the multi-mode operation of the laser may increase the intermodal dispersion in the fiber so as to decrease the available bandwidth for multichannel operation.

Given the above, there is a need for a technique to operate laser diodes at increased optical output levels while constraining the laser to continue to

20 operate in the single-mode regime.

Summary of the Invention

An approach followed in the present invention to overcome the problem of the "kink effect" is to provide a laser having laterally asymmetric losses that discriminate against modes higher than the fundamental mode.

25 One embodiment of the invention is directed to a semiconductor optical device that has a substrate and first and second semiconductor side regions formed over the substrate. The height of the first side region above the substrate is different from a height of the second side region above the substrate. A semiconductor ridge is disposed between the first and second

side regions and over the substrate forming an optical waveguide within the device. The height of the semiconductor ridge above the substrate is greater than the heights of the first and second side regions above the substrate.

Another embodiment of the invention is directed to an optical

- 5 communications system that has an optical transmitter, a fiber optic link coupled to receive optical signals from the optical transmitter, and an optical receiver coupled to the fiber optic link to receive the optical signals. A laser is coupled to inject light into the fiber optic link. The laser includes a substrate having first and second semiconductor side regions formed over the substrate.
- 10 The height of the first side region above the substrate is different from the height of the second side region above the substrate. A semiconductor ridge is formed between the first and second side regions and over the substrate to introduce an optical waveguide within the device. The height of the semiconductor ridge above the substrate is greater than the heights of the first
- 15 and second side regions above the substrate.

Another embodiment of the invention is directed to a semiconductor laser that has a substrate having an upper surface. A lateral direction is defined parallel to the upper substrate surface. One or more superstrate layers are provided on the substrate. An optical waveguide is disposed over the

- 20 substrate to guide light passing between ends of the substrate and defining a fundamental optical mode. First and second sides of the optical waveguide provide optical confinement in the lateral direction. The optical confinement for the fundamental optical mode provided on the first side of the optical waveguide is different from the optical confinement provided on the second
- 25 side of the optical waveguide.

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coupled to inject light into the fiber optic link. The laser includes a substrate and one or more superstrate layers provided on the substrate. An optical waveguide is disposed over the substrate to guide light passing between ends of the substrate. The waveguide defines a fundamental optical mode. First 5 and second sides of the optical waveguide providing optical confinement in the lateral direction. The optical confinement for the fundamental optical mode provided on the first side of the optical waveguide is different from the optical confinement provided on the second side of the optical waveguide.

Another embodiment of the invention is directed to a method of forming 10 a semiconductor device having an asymmetric ridge. The method includes removing material on a first side of a ridge region to a first depth, and removing material on a second side of the ridge region to a second depth different from the first depth, so as to produce the asymmetric ridge in the ridge region.

15 The above summary of the present invention is not intended to describe each illustrated embodiment or every implementation of the present invention. The figures and the detailed description which follow more particularly exemplify these embodiments.

Brief Description of the Drawings

20 The invention may be more completely understood in consideration of the following detailed description of various embodiments of the invention in connection with the accompanying drawings, in which:

FIG. 1 schematically illustrates an optical communications system that includes a laser according to an embodiment of the present invention;

25 FIG. 2 is a block schematic diagram illustrating a frequency selected laser unit according to the present invention;

FIG. 3 illustrates a semiconductor laser with an asymmetric ridge waveguide according to the present invention.

FIG. 4 illustrates a first step in the manufacturing process of forming an asymmetric ridge waveguide on a semiconductor device.

FIG. 5 illustrates a second step in the manufacturing process of forming an asymmetric ridge waveguide on a semiconductor device.

FIG. 6 illustrates a third step in the manufacturing process of forming an asymmetric ridge waveguide on a semiconductor device.

5 FIG. 7 illustrates a fourth step in the manufacturing process of forming an asymmetric ridge waveguide on a semiconductor device.

FIG. 8 illustrates a fifth step in the manufacturing process of forming an asymmetric ridge waveguide on a semiconductor device.

10 FIG. 9 illustrates a sixth step in the manufacturing process of forming an asymmetric ridge waveguide on a semiconductor device.

While the invention is amenable to various modifications and alternative forms, specifics thereof have been shown by way of example in the drawings and will be described in detail. It should be understood, however, that the intention is not to limit the invention to the particular embodiments described.

15 On the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the appended claims.

Detailed Description

In general, the present invention is directed to a semiconductor device
20 that has an asymmetric ridge waveguide. In particular, the material on one side of the ridge is at a different height from the material on the other side of the ridge. A laser formed with an asymmetric waveguide has improved wave-guiding properties in that there is less lateral confinement for higher order modes above the fundamental mode. As a result, the threshold for a higher
25 order mode is higher than in a laser having an equivalent symmetrical ridge, and so the power level at which the output from the laser changes from being single transverse mode to including a higher order transverse mode is increased. Accordingly, the "kink power", the power at which the kink occurs in the L-I curve of the laser, is higher, and the laser may be used to operate in a

single transverse mode at higher power levels. One of the advantages of higher power operation with a single transverse mode is in pumping fiber devices, such as fiber amplifiers or fiber lasers. The occurrence of the kink is usually accompanied with a reduction in the coupling efficiency into the fiber

5 because the higher order mode is less focusable than the fundamental transverse mode. The increase in the kink power, therefore, permits increased amounts of light to be coupled into the fiber device with high efficiency.

A laser having an asymmetric waveguide according to the present invention may be employed in a DWDM communications system 100, 10 schematically illustrated in FIG. 1. The system 100 includes a dense wavelength multiplexed (DWDM) transmitter unit 102 that includes a number of lasers 104a - 104n operating at different wavelengths, $\lambda_1 - \lambda_n$. In addition, one or more spare lasers 105 may operate as a substitute if any of the lasers 104a - 104n fail. The lasers 104a - 104n and 105 may each include modulators for 15 modulating information onto the respective output light beams. The outputs from the lasers 104a-104n, 105 may be combined in a DWDM combiner arrangement 106 and launched as a DWDM signal into an optical fiber communications link 108 that is coupled to a DWDM receiver 110.

The transmitter 102 may also include a pump laser unit 112 for 20 transmitting pump light into the fiber link 108. For example, the pump laser unit 112 may produce pump light having a wavelength, λ_p , that pumps a fiber amplifier. In one embodiment, the pump laser unit 112 generates light at a wavelength that provides Raman gain for the DWDM signal. The pump light and the DWDM signal may both be injected in to the fiber link 108 from the 25 transmitter 102, with the result that the DWDM signal is amplified in the initial portion of the fiber link leaving the transmitter.

The fiber link 108 may include one or more fiber amplifier units 114 to amplify the DWDM signal as it propagates to the DWDM receiver 110. An amplifier unit 114 typically includes a length of fiber that provides gain to the

DWDM signal and one or more pump lasers in a pump laser unit 116. The gain fiber may be, for example a rare earth-doped fiber, such as an erbium-doped fiber amplifier (EDFA), or may be a Raman fiber amplifier (RFA). The pump lasers in the pump laser unit 116 provide pump light at a wavelength

5 appropriate for pumping the fiber amplifier. Where the fiber amplifier is an EDFA, the pump light may have a wavelength of around 980 nm. Where the fiber amplifier is a RFA, the pump light may have a wavelength different from the wavelength of the DWDM signal by an amount equal to the Raman Stokes shift.

10 Other elements, such as isolators, switches, add/drop multiplexers and the like may also be disposed along the fiber link 108. The DWDM receiver 110 demultiplexes the received DWDM signal in a demultiplexer 118 and directs signals at different wavelengths $\lambda_1 - \lambda_n$ to respective channel detectors 120a-120n.

15 A block schematic diagram showing various elements of a pump laser unit 200 that uses a laser according to an embodiment of the present invention is illustrated in FIG. 2. A laser 202 generates an output light beam 204 that is coupled to a fiber 206, typically using a lens system 208 having one or more lenses. The fiber 206 may include a fiber Bragg grating (FBG) 210 that

20 provides feedback to the laser 202 at the selected pump wavelength, λ_p . This helps to maintain the output wavelength of the laser 202 at the desired pump wavelength, λ_p . The output wavelength of the laser may be selected using another technique. In some embodiments, a grating such as a distributed Bragg grating may be integrated with the laser 202, or a FBG or other

25 frequency selective element may be provided at the rear end 212 of the laser 202 to provide frequency selective feedback, thus stabilizing the wavelength of the light 204 output from the laser.

The laser 202 may be any suitable type of semiconductor laser that produces an output at a desired wavelength. For example, to produce output at

around 980 nm for pumping an EDFA, the laser 202 may use an InGaAs quantum well active region grown over a GaAs substrate. To produce an output in the range 1400 nm - 1500 nm for providing Raman gain, the laser 202 may use an InGaAsP quantum well active region formed over an InP substrate.

5 A monitor 214, for example a tap monitor, may be used to monitor the output power from the laser 202. The monitor may be positioned to measure a portion of the laser output, as illustrated, or may be positioned at the back of the laser 202 to measure the power leaking out of the rear end 212. A controller 216 includes the power supply 218 for providing power to the laser

10 202. The power supply 218 may be coupled to receive a power signal from the tap monitor 214, and may regulate the amount of current directed to the laser so as to maintain a constant output power.

The laser 202 is typically mounted on a submount 220 that is thermally coupled to a cooling unit 222 that removes excess heat from the laser 202.

15 15 The cooling unit 222 may be an active cooler, such as a thermoelectric cooler. Where the cooling unit 222 is an active cooler, the controller 216 may include a cooler control unit 224 coupled to control operation of the cooling unit 222.

FIG. 3 illustrates an end-on view of a semiconductor laser diode 300 with an asymmetric ridge waveguide 302. The asymmetric ridge waveguide 302 is shown with a left-hand side of the ridge 302L, having a different height from that of the right-hand side of the ridge 302R. Bonding pads 304 are typically situated on either side of the asymmetric ridge waveguide 302 for making electrical contact to the laser diode 300. The laser diode 300 is formed from a number of superstrate layers 306 formed over a substrate 308. The bottom 20 surface of the substrate 308 typically has a metallization layer 312 for soldering to submount assemblies. The superstrate layers 306 include an active layer 310, which may be a quantum well active layer. The superstrate layers 306 may 25 also include layers that, in tandem with the asymmetric ridge waveguide 302,

provide optical confinement of laser light within the laser diode 300 in the vertical and/or horizontal direction.

The right-hand side of the ridge 302R may be further in depth into the superstrate 306 and may therefore be closer in proximity to the active region 5 310 than the left-hand side of the ridge 302L. The slopes of the ridge surfaces 302L and 302R may be the same, or the slope of the right-hand side ridge 302R may be different from the slope of the left-hand ridge 302L. In this case, the right-hand side ridge 302R may be sufficiently close to the active region 310 so as to generate tight lateral confinement/waveguiding. In contrast, the left-10 hand side ridge 302L may be sufficiently far removed from the active region 310 so that the waveguide provides weak lateral confinement of higher order modes, while still efficiently guiding the fundamental mode. The net result of this asymmetric configuration, with stronger confinement on one side of the waveguide relative to the other side, may result in the waveguide being less 15 efficient in guiding higher order modes than the fundamental lowest order mode of the waveguide, which leads to an increase in the threshold condition for lasing action for the higher order modes. This may allow the laser 300 to be operated at higher single-mode power levels before the so-called "kink effect," indicative of the higher order modes reaching threshold, becomes apparent.

20 Similar results may be obtained if the ridge geometry were reversed, for example, the left-hand ridge 302L may be sufficiently close to the active region 310 to provide tight lateral confinement and the right-hand ridge 302R may be sufficiently far removed to yield weak lateral confinement of the higher order modes.

25 Asymmetric ridge waveguides may be fabricated by a technique which includes two (or more) optical masks and multiple masking steps for the left and right-hand ridge regions. Fabrication of asymmetric ridge waveguides utilizing this technique may require difficult mask-to-mask alignment accuracies on the order of a micron or less.

Another approach to fabricating an asymmetric waveguide laser that employs a single mask and a single masking step is described with reference to FIGs. 4-9. FIGs. 4-9 schematically illustrate a device at different stages of fabricating an asymmetric ridge waveguide according to one particular embodiment of a manufacturing method. FIG. 4 illustrates the first step in the manufacturing process of forming an asymmetric ridge waveguide on a semiconductor device 400. The semiconductor device 400 includes a semiconductor substrate 402 with a superstrate layer 404 fabricated, for example, by an epitaxial process such as molecular beam epitaxial (MBE) growth or metal organic chemical vapor deposition (MOCVD). A photoresist layer 406 is deposited on the upper surface of the semiconductor device 400. A three region optical mask having of a left-hand region 408L, a middle region 408M, and a right-hand region 408R may be placed over the photoresist layer 406. The three regions of the optical mask 408L, 408M, and 408R have different optical transmission efficiencies. To form an asymmetric ridge with a greater depth on the right-hand side of the ridge, the right-hand side of the optical mask 408R may have a transmission efficiency near 100%, whereas the left-hand side of the mask 408L may have a transmission efficiency less than 100%. The middle region of the mask 408M typically is optically opaque at the exposure wavelength, with nearly 0% transmission.

The top surface of the semiconductor device 400 may be illuminated with equal intensities of light 410 incident upon all three regions of the optical mask 408L, 408M, and 408R. Sufficient light 410 may be delivered through the mask such that the photoresist under the right-hand side of the mask 408R may be fully exposed while the photoresist under the left-hand region 408L may be only partially exposed. Under these circumstances, the photoresist under the middle region 408M may be effectively unexposed. After delivery of the illumination light 410, the optical mask may be removed.

FIG. 5 illustrates the results of the second step in the manufacturing process. In the second step, a developer solution may be applied to the top surface of the semiconductor device 500, which totally removes the photoresist on the top right-hand side of the device 500. The left-hand region of the 5 photoresist 506L is partially removed since it was only partially exposed. The middle portion 506M of the photoresist remains unexposed, and so its thickness is effectively unchanged from its original thickness.

FIG. 6 illustrates the results of the third step in the manufacturing process. A chemical etchant has been applied to the top surface of the device 10 600 and etching has occurred to form the beginnings of the right-hand side ridge 608R. At this stage, the remaining left-hand 506L and mid-region 506M photoresist has protected the remainder of the top surface from chemical etching.

FIG. 7 illustrates the results of the fourth step in the manufacturing 15 process. In this step, additional UV light has been delivered to the top surface of the device 700 to fully expose the left-hand region of the photoresist (not shown) and partially expose the mid-region 506M of the photoresist. The top surface is then treated with developer to completely remove the left-hand portion of the photoresist but leave behind a partial thickness of the mid-region 20 photoresist 506M.

FIG. 8 illustrates the results of the fifth step in the manufacturing process. In this step a chemical etchant has been applied to the top surface of the device 800 and etching has occurred to form the final geometry of the left-hand side region 808L and right-hand side region 808R of the asymmetric 25 ridge.

FIG. 9 illustrates the results of the sixth and final step in the manufacturing process of forming an asymmetric ridge waveguide on a semiconductor device 900. In this step the remaining photoresist on the middle region is removed by applying a chemical agent such as acetone. The

semiconductor device 900 may now undergo additional processing steps to fabricate, for example, bonding pads, bottom-surface metallization and the like.

An advantage of this approach is that a single masking step is required, thus simplifying the manufacturing process of the asymmetric ridge by avoiding

5 the need to align a second mask with a first exposed portion of the semiconductor device.

As noted above, the present invention is applicable to semiconductor devices and is believed to be particularly useful for semiconductor devices with an asymmetric waveguide. The present invention should not be considered

10 limited to the particular examples described above, but rather should be understood to cover all aspects of the invention as fairly set out in the attached claims. Various modifications, equivalent processes, as well as numerous structures to which the present invention may be applicable will be readily apparent to those of skill in the art to which the present invention is directed

15 upon review of the present specification. The claims are intended to cover such modifications and devices.